2005-01-3399

Conceptual Design of Current Technology and Advanced Concepts for an Efficient Multi-Mach Aircraft

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ABSTRACT

A design process is formulated and implemented for the taxonomy selection and system-level optimization of an Efficient Multi-Mach Aircraft Current Technology Concept and an Advanced Concept. Concept space exploration of taxonomy alternatives is performed with multi-objective genetic algorithms and a Powell's method scheme for vehicle optimization in a multidisciplinary modeling and simulation environment. A dynamic sensitivity visualization analysis tool is generated for the Advanced Concept with response surface equations.

INTRODUCTION

In recent years the aerospace community has strongly embraced the idea to look into the future and identify key concepts and technologies that need to be pushed forward today. For this purpose government entities identify notional systems that respond to national and international challenges, specify desired future capability goals and determine the technological objectives to attain these goals. This paper describes the research efforts conducted on an Efficient Multi-Mach Aircraft (EMMA), one of three vehicle concepts of the Supersonic Aircraft (SSA) sector of NASA's Vehicle Systems Program (VSP). Current technological capabilities are quantified through the modeling of a Current Technology Concept (CTC) which serves as a state of the art reference system. An Advanced Concept (AC) is similarly modeled but is representative of a 15 year technology advancement by virtue of the aforementioned technological objectives. The performance metrics of the AC are used to validate the desired capability goals and to implement a sensitivity analysis between the system performance and the technology objectives.

MOTIVATION

The EMMA is a critical vehicle concept whose design responds to important challenges.

1) To date the U.S. has failed to successfully design and produce a viable supersonic civil transport. Previous efforts such as the High Speed Civil Transport (HSCT) under NASA's HSR program did not overcome the aggressive performance and economic goals and were ultimately terminated after funding was exhausted.

2) Current environmental regulations impose stringent constraints regarding sonic boom and emissions. Said regulations have been ignored in previous supersonic programs such that of the Concorde, whose fleet was recently retired.

3) The United State's supremacy in the international aerospace arena is currently challenged by European competitors. Recently Japan and France have unveiled plans to work together in the development of a successor for the Concorde with an initial three-year program funded and supported by companies from both countries [1].

DESIGN APPROACH AND METHODS

The approach adopted in this complex problem is based on design for affordability [2] which addresses the "strong 'cost-knowledge-freedom' dependency from conceptual design to production which can significantly impact the life cycle of a system, specifically, the life cycle costs". This approach results from the design paradigm shift described by Kirby and Mavris [3] that advocates the selection of higher-fidelity tools and multidisciplinary methods early in the design process.

The EMMA design emphasis on efficient operations for both subsonic and supersonic speeds imposes a complex design challenge: integrating the naturally incompatible design trends of both Mach regimes in a single concept. Particular attention is given to the selection of an adequate vehicle taxonomy and system level parameter values, expected to be highly correlated with the sizing mission definition and the vehicle requirements. Concept space exploration of optimal taxonomies for complex systems has been researched in the past through Genetic Algorithms [4][5] and recent work has been directed towards applications on aircraft [6][7][8].

The sensitivity analysis is based on Response Surface Methodology (RSM), a statistical method readily found in literature [9][10]. Response Surface Equations (RSE) have been used in the past for meta-modeling aircraft response metrics, technology infusion on advanced aircraft systems [11], and applications in robust solutions and probabilistic simulations [12].

DESIGN PROCESS FORMULATION

Figure 1 depicts the series of steps taken to formulate and model an EMMA CTC and AC with which a sensitivity analysis is produced. The following sections describe these steps.

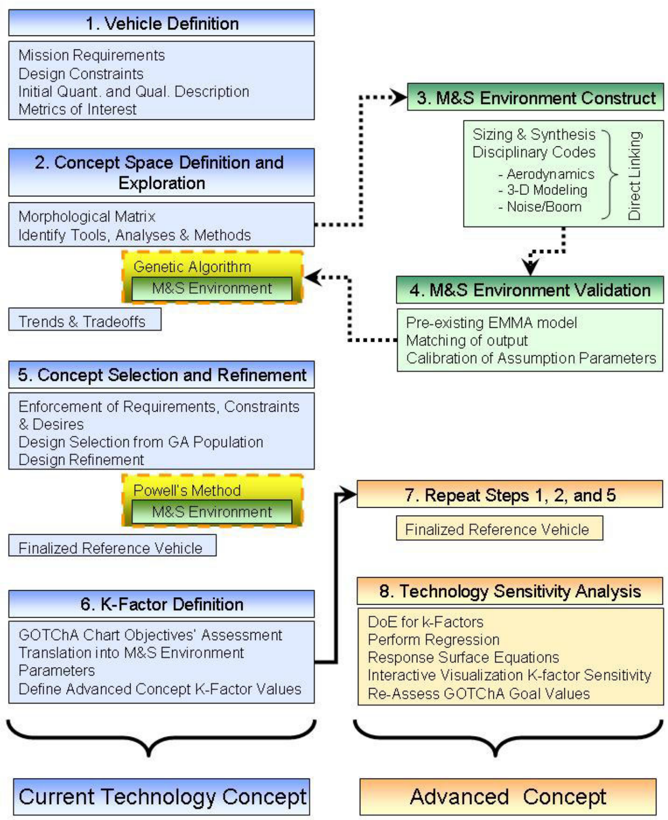

Figure 1. Design process formulation flowchart

VEHICLE DEFINITION

The design process of the EMMA begins by observing the mission requirements, design constraints and customer desires of the notional vehicle as provided by the customer. This information is used by the designers to construct a concept vehicle definition that reflects a qualitative understanding of the system, to define a sizing mission and to specify what metrics and top level control variables will be used.

MODELING & SIMULATION ENVIRONMENT: CREATION AND VALIDATION

A Modeling and Simulation Environment (M&SE) is created by selecting and adequately integrating all tools used to model any aspect of the system under study. Selection criteria for these tools are based on the metrics identified in the vehicle definition and the control variables chosen by the designer. The vehicle definition of both the CTC and the AC should be taken into account when choosing the tools that will comprise the M&SE since the two systems may not share all metrics of interest but share the M&SE. This environment should be validated by modeling a system comparable to the one under study for which pre-existing information is available.

CONCEPT SPACE DEFINITION AND EXPLORATION

In the present study ‘concept space’ is defined as the discontinuous set of all possible solutions of a design problem irrespective of taxonomy or architecture. In order to define the concept space a morphological matrix containing possible alternatives for vehicle taxonomy characteristics is used as a starting point to create a morphological breakdown which follows a top down decomposition from system (EMMA) to parameter values (e.g. 35 deg sweep). Rules for combinations are set at this point to ensure that no physically incompatible alternatives are put together. The definition of the concept space also identifies the direction of improvement in the GA for each one of the metrics of interest. The Pareto optimal or non-dominated solutions resulting from the GA make up a hyper-surface along which improvement in one objective requires a sacrifice in another. Once this front has been found, the designer can use it to explore the relationships and tradeoffs between the objectives across different concepts alternatives and identify performance limits of a particular technological level so that intelligent decisions can be made.

CONCEPT SELECTION AND REFINEMENT

The designs resulting from the concept space exploration are subjected to all design constraints, thus reducing the number of designs to a manageable amount of feasible solutions. The designer selects the one that provides a compromise that best satisfies requirements and customer desires. With the selection of a design as a reference vehicle the general configuration of the EMMA is fixed. In the case where no feasible designs result after implementing all constraints concurrently, the constraints are gradually relaxed until a feasible design appears. A Powell’s optimization method [13] is implemented to optimize the selected vehicle within the vicinity of its design space. In the context of this study ‘design space’ is defined as the continuous set of all possible solutions for a fixed taxonomy. The result, after confirming that all constraints are still concurrently met, is the finalized reference vehicle.

K-FACTOR DEFINITION

In order to model customer-defined objectives for the AC a series of system level enhancements are modeled via multipliers within the analysis codes in the M&SE. These multipliers, known as k-factors, are continuous scalars that adjust/scale system metrics to reflect desired improvements or the application of a technology [12]. Examples of such k-factors are weight reduction, drag reduction and fuel consumption reduction factors. When a k-factor has a value of one (1.0) it represents the current technology level and it yields no scaling to the system level parameters. In some exceptional instances the SOA level may have values other than 1.0 but rarely will they deviate from the nominal value by more than 10%. The set of k-factors and their respective values chosen for a sensitivity analysis is purely problem dependent, driven by the system level goals provided by the customer determining the AC's capabilities.

SENSITIVITY ANALYSIS

In the sensitivity analysis the performance of the AC as quantified by the metrics of interest is verified against the customer-defined system-level goals for the AC, providing a measure of any overestimation or underestimation of the objective values with respect to the goals. The sensitivity of the goals to the objectives is observed through RSE's which allow for graphic representation of the multi-dimensional relationship between goals and objectives and Pareto analysis for impact assessment. For the generation of RSE's only the k-factors are allowed to vary within a reasonable range for the fixed design of the AC. Top-level sizing parameters TOGW, thrust-to-weight ratio (T/W), and wing loading (W/S) are also varied to observe the coupling between the variation of k-factor values and basic scaling of the AC's final configuration. The relationships between metrics and k-factors that result define the k-space.

The sensitivity analysis provides maximum transparency to the k-space and gives very direct indications of what k-factors are most effective and to which ones the Advanced Concept EMMA is least sensitive to. This assessment also suggests what goals need be revised by the customer, relaxing the target value or adjusting it for more aggressive improvements. In the context of future research effort installments this task also serves as an initial assessment on what specific technologies should be pursued in the generation and evaluation of a technology portfolio.

IMPLEMENTATION

EMMA CURRENT TECHNOLOGY CONCEPT VEHICLE DEFINITION

The Current Technology Efficient Multi-Mach Aircraft is conceived as a Multi-Mach, medium-capacity, narrow-body (single-aisle), four-engine, civil transport with 50-50 subsonic-supersonic trans-Pacific range. This range is specified at 5,500 [nm] as a mission requirement. Field performance mission requirements specify that the EMMA CTC take off within 10,500 [ft]. A nominal number of 175 passengers (PAX) is fixed as a system level requirement. Although a nominal PAX value is defined this parameter was varied to identify trends and trade-offs. The sizing mission for the EMMA is depicted in Figure 2. Although the main profile of the mission is fixed some operational parameters such as supersonic Mach number and cruise altitudes are allowed to vary as control parameters in order to identify optimum combinations of vehicle taxonomy and operational mission parameters.

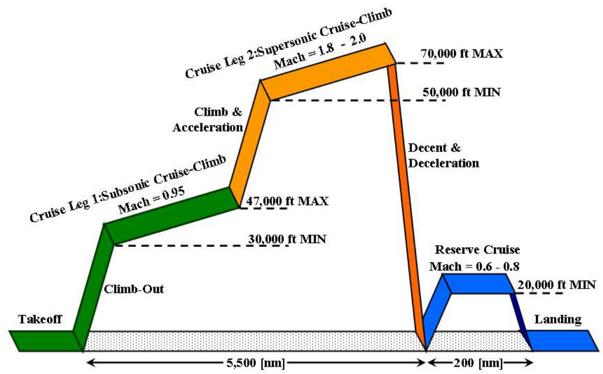

Figure 2. EMMA sizing mission profile

Given the number of passengers and off-design fuel consumption considerations, the vehicle is expected to be in the take-off gross weight (TOGW) range of 400,000 [lb] and 750,000 [lb]. These values are used as limits to the input TOGW. Weight minimization is explicitly set as a customer desire by the customer. The metrics of interest identified for the Current Technology EMMA concept are Range [nm], TOFL [ft] and TOGW [lb]. Additionally the number of passengers (PAX) and the cruise Mach number are included for tracking purposes. Maximization of Mach number (within the allowable range) is stated as a customer desire. Also, the zero trim assumption during cruise requires the tracking and minimization of stability margin absolute value. To guarantee that all metrics of interest are identified at this point before formulating the M&SE the requirements for the AC are observed at this point. The AC range is specified at 5,500 [nm]. The AC must take off over a field length no greater than 8,500 [ft], should not exceed a sonic boom initial over pressure (IOP) of 0.5 [psf], and it should have a sonic boom perceived loudness (PL), measured in audible (or A-weighted) Decibels [dBA], that allows for overland supersonic operations. Given the AC requirements IOP [psf] and PL [dBA] are added as metrics of interest. Additionally fuselage length and supersonic cruise altitude are included for tracking purposes.

M&S ENVIRONMENT: FORMULATION AND VALIDATION

The main disciplines encompassed in this study are geometric representation, aerodynamics, weights, propulsion, stability and control, and mission analysis. Lack of commonality in the input and output format of the different tools did not allow for an efficient direct linking in traditional frameworks and thus an alternative approach using MATLAB™ [14] was undertaken. The architecture of the MATLAB code integrating the various analyses is shown in Figure 3.

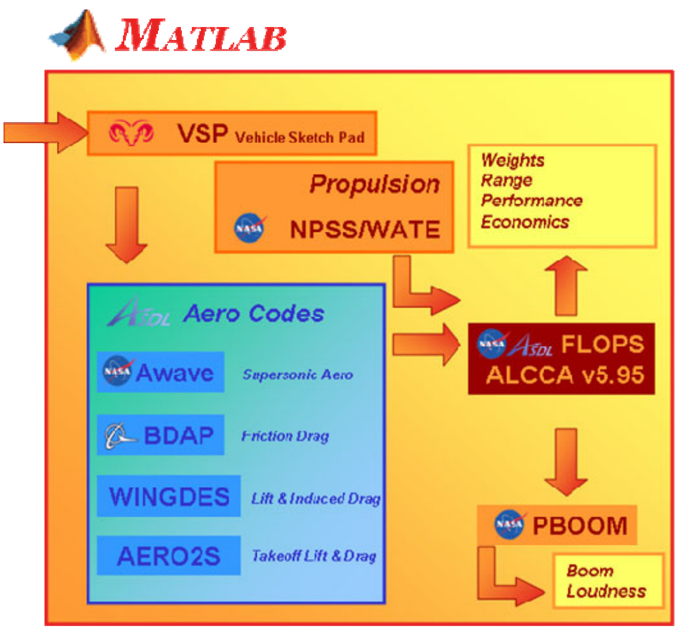

Figure 3. Architecture of modeling and simulation environment

Geometric representation for the EMMA was performed with the Vehicle Sketchpad (VSP), developed by NASA. This tool provides medium fidelity parametric geometry representation at the expense of low computational resources. The geometric model was used to generate the aerodynamic data of the design. A number of tools based upon linearized methods were used to calculate properties such as supersonic wave drag (AWAVE)[15], skin friction drag (BDAP)[16], induced drag (WINGDES), and low speed aerodynamics (AERO2S) [17]. In this research a fixed propulsion system generated at NASA GRC using NPSS and WATE was used. The system consists of an air induction system, a low bypass ratio mixed flow turbofan engine with design Mach number 2.0, and a mixer-ejector nozzle. The engine model is a rubberized-type deck which allows for photographic scaling of the geometric dimensions and weights of the propulsive system elements according to a prescribed required installed thrust. The baseline engine weighs no more than 23,000 [lb] and generates a maximum sea-level static thrust of approximately 50,000 [lb].

The propulsion and aerodynamic data are fed into the Flight Optimization System (FLOPS) [18], used to calculate the vehicle's range and field performance as well as the weights analysis. The weights and balance data produced also yield stability margin envelopes along with aerodynamic data. Weight data is also used for calculation of sonic boom loudness in one last aerodynamic code, PBOOM [19]. This code provides a pressure signature of the system in the far field and calculates the loudness in dBA.

The M&SE was validated using a preexisting model provided by the customer. The verification reference vehicle is based upon the supersonic air transport described by Shields and Hicks[20] ,resized to carry 175 passengers over a 5500 nm 50% Mach 0.95, 50% Mach 2.0 mission. The propulsion model used was the same one implemented for the EMMA. Results indicated that the vehicle weight breakdown for the two models was within a 1% difference. Furthermore it was determined that the aerodynamic behavior of the two models presented consistent similarity. In general the M&SE was successfully validated and deemed adequate for the present EMMA design study.

EMMA CURRENT TECHNOLOGY CONCEPT SPACE DEFINITION AND EXPLORATION

For the EMMA CTC the propulsion system is fixed and a single fuselage type is considered, and thus only wing planform and tail configuration were included in the morphological matrix, as shown in Figure 4.

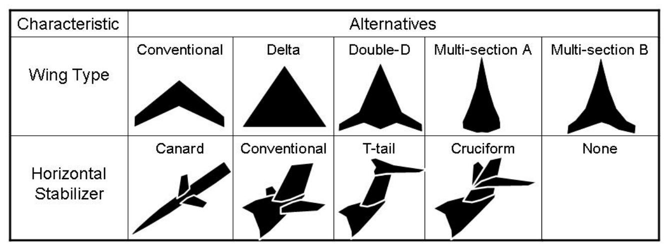

Figure 4. Morphological matrix for EMMA tail and planform

All combinations are assumed to have a vertical tail. It is also assumed that no more than one horizontal tail and no more than one wing planform can be set per design. The GA ran the M&SE for 120 generations with a population of 1,200 designs. In this GA, designs are defined to evolve/improve in terms of minimization or maximization of the metrics of interest as shown in Table I.

Table I. Objective specification for CTC genetic algorithm

Parameter	Direction of Improvement
Range	Max
TOFL	Min
Mach	Max
TOGW	Min
Static Margin	Min
PAX	Track

The distribution of taxonomy combinations in the final population is shown in Table II. The double delta configuration overwhelmingly dominated the final generation of the GA, which is indicative of the benefits of the double delta as a subsonic/supersonic planform. No conventional tail configurations resulted in the final population suggesting unfavorable tail sizing, weight balancing and drag-related reduction of range capabilities.

Table II. Taxonomy combinations in final population of genetic algorithm for CTC

Wing Type		Horizontal Tail Type	
Double Delta	1197	None	293
Multi-Section	3	Canard	417
		T-Tail or Cruciform	490
Total	1200	Total	1200

The concept space exploration was visualized by means of 2-D objective plots where the designs were color coded according to taxonomy. The Pareto fronts were outlined and used to visually identify design trends and tradeoffs. An example of these plots is shown below in Figure 5 for Range vs. TOFL.

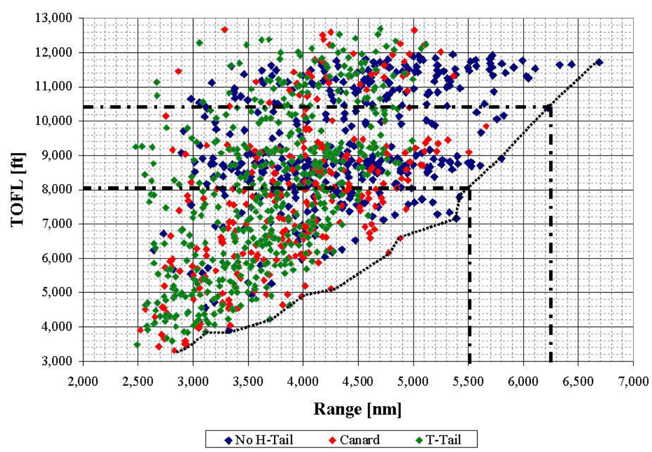

Figure 5. Range vs. TOFL plot for final population of CTC genetic algorithm

An overall increase in range with Mach number was observed, maximized with the configuration with no horizontal tail. A strong relationship was observed between number of passengers (PAX) and range where a 17.5 [nm] decrease per additional passenger occurs for the 120 to 200 PAX/ 6,500 [nm] to 5,100 [nm] range. For the nominal PAX value of 175, the Pareto front suggests a corresponding range value very close to 5,500 [nm]. The Pareto front of the TOFL vs. range plot is defined by T-tail and canard alternatives for the low TOFL-low TOGW region, and by the tail-less alternative in the high TOFL-high TOGW region. For the required range of 5,500 nm TOFL values as low as 8,000 [ft] were found.

EMMA CURRENT TECHNOLOGY CONCEPT SELECTION AND REFINEMENT

Using a Graphical User Interface (GUI) constructed for this study the entire design population was visualized and used to implement the following design constraints:

Range > 5,500 [nm]; TOFL < 10,500 [ft]; PAX>175

Of the 1,200 designs in the concept space, none concurrently satisfy these three constraints. After relaxing the PAX constraint to 170 a single design satisfying all constraints was found. The metrics of interest of the tail-less double delta are shown in Table III.

Table III. Metrics of interest for CTC design

Metric	Value
Range [nm]	5,645
TOFL [ft]	10,499
Mach	1.94
TOGW [lb]	750,000
PAX	173
Static Margin	4.9

This candidate design was set as the starting point in the Powell's Method routine developed for the design space refinement task. The optimization is initiated by setting goal values for the various metrics and a weighting scenario with which the code will give priority to meeting certain metrics' goals over others. The objective minimized by the Powell's routine is a penalty term given by

$$\text{Penalty} = \sqrt{\sum_{i=1,n}\left(\frac{\text{Calculated Metric Value}_i \text{ - Target Metric Value}_i}{\text{Norm}_i}\right)^2}$$

To increase the importance of a metric the norm value is reduced. For the CTC candidate optimization the target and normalization values shown in Table IV were implemented

Table IV. CTC candidate design optimization target and normalization values

Metric	Target Value	Norm Value
Range [nm]	5,500	20
TOFL [ft]	10,500	20
Mach	2.0	0.1
TOGW [lb]	650,000	1,000
PAX	175	1
Static Margin	0	1

The M&SE was executed for approximately 500 optimization iterations. The resulting design was checked to make sure that the overall configuration and characteristic values were sound. The resulting design is the final CTC for which the metrics of interest and 3-view are shown in Table V and Figure 6 respectively.

Table V. Metrics of interest for finalized CTC reference vehicle

Metric	Value
Range [nm]	5,502
TOFL [ft]	10,256
Mach	2.0
TOGW [lb]	645,570
PAX	175
Static Margin	0.0

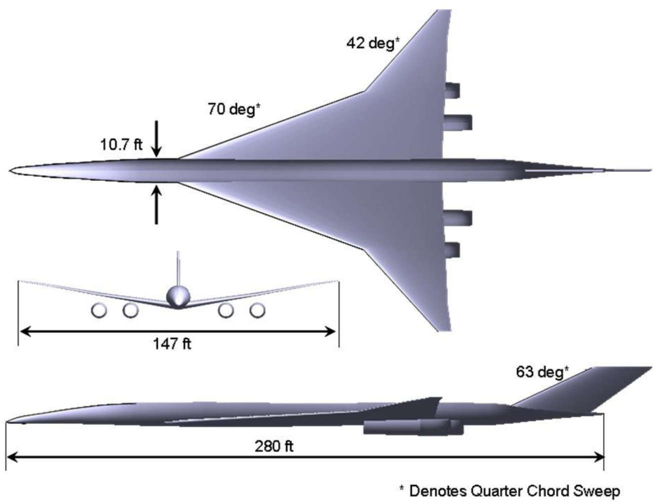

Figure 6. 3-view of the finalized CTC reference vehicle

The mission block time is 8 hours with a total flight time of 7 hrs 47 min. A detail mission breakdown is provided in Figure 7 where weight, block time, altitude and range are tracked.

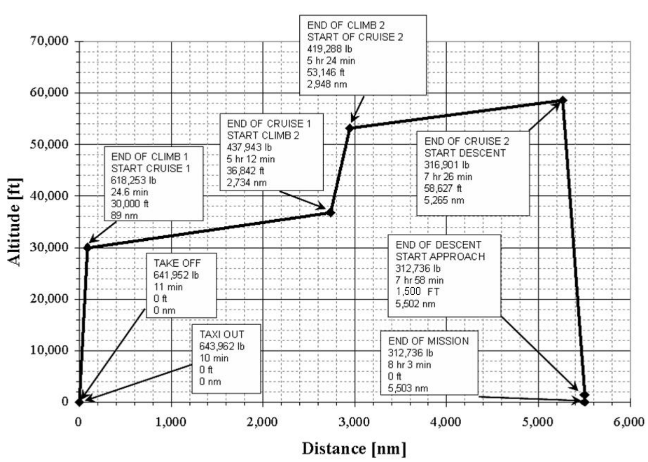

Figure 7. CTC reference vehicle mission breakdown

The CTC has a reference wing area of 7,938.76 [sqft] yielding a maximum wing loading at takeoff of 81.32 [psf]. The four engines produce 38,734 [lb] each resulting in a total thrust to weight ratio of 0.24 at takeoff. The overall configuration has a lift coefficient varying between 0.15 and 0.2 for the subsonic cruise leg, and of approximately 0.09 for supersonic cruise. The weight breakdown of the CTC, shown in Table VI, indicates that more than half of the ramp gross weight is mission fuel, suggesting that fuel consumption reduction is a critical area of improvement for the AC.

Table VI. Weight Breakdown for the EMMA CTC

Element	Percent W_{Reff} [%]	Weight [Lbs]
STRUCTURE TOTAL	19.13	123,483
PROPULSION TOTAL	11.79	76,142
SYSTEMS AND EQUIPMENT TOTAL	6.53	42,170
WEIGHT EMPTY	37.45	241,795
OPERATING WEIGHT	38.55	248,876
ZERO FUEL WEIGHT	44.22	285,451
MISSION FUEL	55.78	360,118
RAMP GROSS WEIGHT	100	645,569

DEFINITION OF TECHNOLOGY K-FACTORS FOR ADVANCED CONCEPT

Criteria for k-factor definition/selection and value assignment follow from the Goals, Objectives, Technical Challenges and Approaches (GOTChA) charts for the EMMA 15 year vehicle capabilities [21]. Two main areas of these charts are airframe and propulsion. This study dealt mainly with the airframe portion although a few propulsive k-factors are included. The goals and objectives values of the GOTChA chart used for the definition of the k-factors are presented in Table VII.

Table VII. Goals and objectives for the EMMA AC

	Goals		Objectives
1	Mach 2.0 Supersonic Cruise L/D = 10.5	1	Skin Friction Reduction by 25%
		2	Wave + Lift Dependent + Propulsion Integration Drag Reduction by 20%
		3	Excrescence & Trim Drag Reduction by 50%
2	Airframe Weight Fraction = 0.38	4	Subsystem Weight Fraction Reduction by 25%
		5	Structural Weight Fraction = 0.22
		6	Acceptable Sonic Boom
3	Sonic Boom Annoyance Reduction to Allow Overland Supersonic Flight	7	Define Acceptable Sonic Boom Metrics & Levels
		8	Do Not Exceed Boom Goal In Normal Aircraft Operations
4	Low Speed Aero Performance Climb-out L/D=8.5 Takeoff CL = 1.25	9	Increase available CL by 25% - Increase Climb-out L/D by 25%
5	TSFC (installed) @ M 2.0 = 1.1	12	Decrease Fuel Burn
6	Thrust to Weight (Installed Inlet/Engine/Nozzle) = 6.0	14	Acoustic Nozzle Weight per Unit Airflow Reduction by 5/12
		15	Inlet Weight per Unit Airflow Reduction by 4/9

With this list of goals and objectives in mind the k-factors for the Advanced Concept and their corresponding values were defined and iterated upon with the customer. The list is presented in tabular form in Table VIII. For each k-factor a description and chosen value are provided as well as the objective it addresses.

Table VIII. K-factor descriptions and values for advance concept

k-Factor	Reduction/Increase on	Value	Objective
K.sfcsub	subsonic fuel consumption	0.9	12
K.sfcsup	supersonic fuel consumption	0.9	12
K.cdf	skin friction drag	0.75	1
K.cdw	wave drag	0.8	2
K.cdi	drag due to lift	0.8	2
K.LDTO	lift/drag ratio at takeoff	1.25	9
K.suction	percentage of leading edge thrust	0.92	9
K.wingweight	wing weight	0.78	5
K.fusweight	fuselage weight	0.78	5
K.empweight	empennage weight	0.78	5
K.inlweight	inlet weight	0.625	15
K.engwt	engine weight	0.85	14
K.nozwt	nozzle weight	0.6	14
K.furn	engine furnishings weight	0.75	4
K.fuelsystemwt	fuel system weight	0.75	4
K.gearwt	landing gear weight	0.75	4
K.surfcntrlweight	control surface weight	0.75	4
K.APUwt	APU weight	0.75	4
K.instrweight	instruments weight	0.75	4
K.hydrweight	hydraulic system weight	0.75	4
K.elecweight	electric system weight	0.75	4
K.avionicsweight	avionics weight	0.75	4
K.ACweight	air conditioning system weight	0.75	4

EMMA ADVANCED CONCEPT VEHICLE DEFINITION

The EMMA Advanced Concept has the same vehicle definition and sizing mission profile as the CTC, taking into account the 15 years of technological advancement with respect to the CTC. Requirements for the AC were provided previously with the CTC vehicle definition. The Advanced Concept features significant weight reductions on structural elements, subsystems, and required fuel, shifting the expected TOGW range between 350,000 [lb] and 550,000 [lb]. Weight minimization is explicitly set as a customer desire by the customer.

EMMA ADVANCED CONCEPT SPACE DEFINITION AND EXPLORATION

The morphological matrix and morphological breakdown for the Advanced Concept is based on the same assumptions, considerations, and rationale as those presented in the previous section for the CTC. The symmetric swing wing alternative was added to explore tradeoffs and potential benefits. A 20% wing-element weight penalty was used and is based on estimates by Raymer (19%)[22] and Beissner (17.5% for pivot and 3-5% for hydraulics)[23]. The GA was run with the assumptions and settings utilized for the CTC. In this GA, designs were defined to evolve/improve as shown in Table IX.

Table IX. Objective specification for AC genetic algorithm

Parameter	Direction of Improvement
Range	Max
TOFL	Min
Mach	Max
TOGW	Min
Static Margin	Min
PAX	Track
Length	Track
PL	Min
IOP	Min

In the final population, the distribution at the alternative level was found to be completely dominated by double delta and T-tail/cruciform combination designs. It was observed that all designs with a range of 5,500 [nm] lie behind the Pareto front and were found to have TOGW values as low as 350,000 [lb] (corresponding to the lower specification limit for TOGW) and TOFL values as low as 5,000 [ft] suggesting that k-factor enhancements easily meet performance requirements. When observing the tradeoff between PAX and range the AC was found to reduce range by 19 [nm] per additional passenger from 4,800 [nm] to 8,000 [nm].

There are a number of elements driving the sonic boom loudness, the most important being Mach number, altitude, weight and geometry/taxonomy. For the AC the IOP and PL were calculated for the beginning of the supersonic cruise leg, providing a worst case scenario where cruise-climb altitude is the lowest and the instantaneous weight is greatest. It has been proven that IOP and PL reduction is attainable via geometric manipulation of the system effectively modifying the far field pressure wave from an N-type signature to a ramped signature [24]. PL is a frequency-weighted metric [25] and is more representative to human response than IOP, establishing its preference for sonic boom performance analysis.

To support the selection of the double delta and t-tail configuration for the AC taxonomy the boom loudness performance of the different taxonomic alternatives in the CTC final GA population were observed. It was observed that designs could roughly be classified into one of three main configuration types :

Configuration Type 1: low wing loading double delta with no horizontal tail.

Configuration Type 2: low wing loading double delta wing planform with a canard.

Configuration Type 3: high wing loading double delta wing planform with a T-tail

It was observed that Configuration Type 3 which composes the entire AC GA population potentially creates ramping effects for the initial and second overpressures effectively reducing IOP and PL. Observation of initial supersonic cruise altitude effects on PL indicate that a significant drop occurs beyond 61,000 [ft]. An important grouping of designs about 66,000 [ft] was found and suggests that the GA encountered a compromise value for cruise altitude impacting sonic boom loudness and other metrics of interest. Pareto front observations relating PL and fuselage length confirm expected trends where lower PL values are attained with longer vehicles. The lower bound values of PL are between 85.5 [dBA] and 86.5 [dBA], and are attained with fuselage lengths between 280 [ft] and 300 [ft]. Range and sonic boom loudness were both identified to be inversely proportional and highly dependent on vehicle weight and taxonomy.

EMMA ADVANCED CONCEPT SELECTION AND REFINEMENT

The selection process for the AC design is the same as that for the CTC, using the constraint capability of the GUI. To attain a favorable design for optimization some constraints relaxation and modification were performed yielding the set show below.

Range > 5,500 [nm]; TOFL < 8,500 [ft];

TOGW < 450,000 [lb]; PAX >170; IOP < 0.5 [psf];

PL < 88 [dBA]; Mach > 1.90

With these constraints a single feasible design resulted, for which the metrics of interest are shown in Table X.

Table X. Metrics of interest of AC candidate design

Metric	Value
Range [nm]	5,890
TOFL [ft]	7,552
Mach	1.93
TOGW [lb]	410,060
Stab. Margin	2.0
Length [ft]	295
PL [dBA]	86.97
IOP [psf]	0.467
PAX	172

The goal values and norm vector used for the refinement task are presented in Table XI.

Table XI. Objective and normalization values for AC optimization

Metric	Target Value	Norm Value
Range [nm]	5,500	1
TOFL [ft]	7,552	70
Mach	2.0	0.1
TOGW [lb]	385,000	1,000
PAX	175	0.1
Length [ft]	280	5
IOP [psf]	0.47	0.05
PL [dBA]	85	0.1

Powell's method was executed for approximately 450 iterations after which all the calculated metrics of interest converged to a final value. The overall configuration and characteristic of the design were checked for reasonableness. The resulting design is the Advanced Concept of the EMMA. The metrics of interest of the AC and a 3-view of the concept are shown in Table XII and Figure 8 respectively.

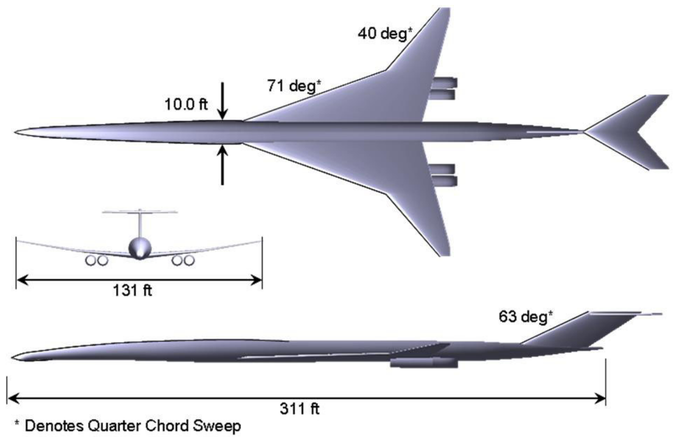

Figure 8. 3-view of finalized AC reference vehicle

Table XII. Metrics of interest for AC reference vehicle

Metric	Value
Range [nm]	5,500
TOFL [ft]	7,452
Mach	2.0
TOGW [lb]	389,080
PAX	176
Length [ft]	311
IOP [psf]	0.476
PL [dBA]	85.76

The AC reference vehicle has a range capability of 5,500 [nm] cruising at mach 0.95 and 2.0 respectively. It transports 176 passengers of which 20 are in first class. The mission flight time is 8 hrs 8 min. A detail mission breakdown is provided in Figure 9 where weight, block time, altitude and range are tracked.

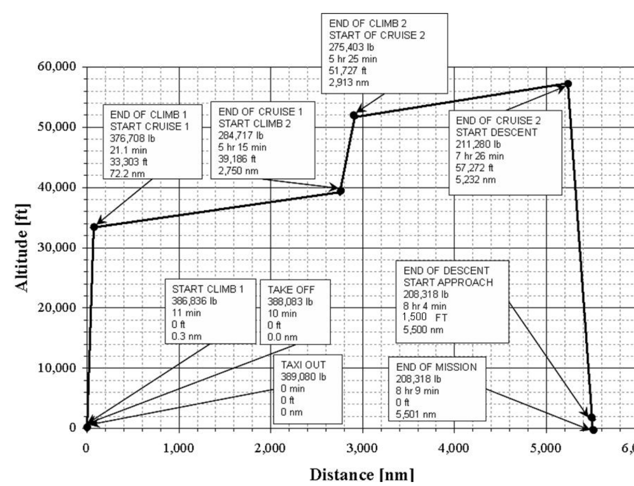

Figure 9. AC reference vehicle mission breakdown

The Advanced Concept reference vehicle has a wing area of 5,512 [sqft] thus yielding a maximum wing loading at takeoff of 70.59 [psf]. The four engines produce 26,702 [lb] of thrust each which result in a vehicle thrust to weight ratio of 0.2745 at takeoff. The overall configuration has a lift coefficient varying between 0.1552 and 0.2 for the subsonic cruise leg and approximately 0.0797 for supersonic cruise. The weight breakdown of the AC, shown compared to that of the CTC in Table XIII, clearly shows the benefits of the weight reduction k-factors. The reduction in supersonic and subsonic fuel consumption reduced the mission fuel weight by over 163,000 [lb]. The Ramp Gross Weight was reduced by approximately 40%. Both systems however have very similar breakdowns in terms of percent contributions of each weight group to the total ramp gross weight.

Table XIII. Weight breakdown and comparison for AC

Element	Advanced Concept		Current Technology Concept	
	Percent W_{Reff}	Weight [lb]	Percent W_{Reff}	Weight [lb]
STRUCTURE TOTAL	20.69	80,499	19.13	123,483
PROPULSION TOTAL	9.77	37,995	11.79	76,142
SYSTEMS AND EQUIPMENT TOTAL	7.8	30,359	6.53	42,170
WEIGHT EMPTY	38.26	148,853	37.45	241,795
OPERATING WEIGHT	40.01	155,658	38.55	248,876
ZERO FUEL WEIGHT	49.46	192,442	44.22	285,451
MISSION FUEL	50.54	196,638	55.78	360,118
RAMP GROSS WEIGHT	100	389,080	100	645,569

SENSITIVITY ANALYSIS

To generate the RSE's for the sensitivity analysis all the k-factors, TOGW, thrust loading and wing loading are set as control variables. The value range for the k-factors was defined at its minimum with the values used for the AC, and at its maximum with the values used for the CTC. The ranges for the scaling parameters, presented in Table XIV, are based on the values of the Advanced Concept reference vehicle and were iterated upon to yield a good balance between k-space flexibility in the metrics of interest and meta-model fit and representation accuracy.

Table XIV. Value range for scaling parameters in sensitivity analysis

Sizing Parameter	Minimum	Maximum
TOGW [lb]	370,000	410,000
Wing Loading [psf]	67.5	80
Thrust Loading	0.26	0.32

A latin-hypercube design of experiments with 350 samplings for the 25 control variables was generated and optimized to reduce correlation leading to inherent regression error. Corner/extreme points were artificially inserted to adequately define the control variable value ranges. The experiments were run in the MS&E and results were imported into the statistical software package JMP™ [26] for regression of the RSE's. Overall the model representation error (MRE) distributions and the statistical parameters suggested good model representation / prediction capabilities and the RSE's were deemed accurate for the sensitivity analysis.

Using the built in Pareto analysis in JMP™ the variability of each of the metrics of interest was decomposed into each of its contributions from k-factors and scaling parameters. The plot for Range shows that aerodynamic and fuel consumption k-factors have the most relevant impact. TOFL was seen to depend very strongly on the sizing parameters T/W and W/S. Aerodynamic improvements for take off such as the factor on $(L/D)_{TO}$ also score high and follow expected behavior of this type of system. Initial Overpressure is strongly affected by sizing ratios T/W and W/S, friction drag coefficient reduction and lift to drag ratio enhancements confirming the sensitivity to geometry, lift distribution and consequently weight. Perceived Level was observed to be highly dependent on wing loading and TOGW, then on the k-factor for the lift dependent drag coefficient, and then by the entire suite of weight reduction factors.

The RSE's were activated in the dynamic Prediction Profiler visualization workspace within JMP™. By manually changing the value of one of the k-factors or scaling parameters all the plots for the metrics of interest are updated to represent a slice of the k-space. The profiler was used for the detailed analysis of the different sensitivities and represents in itself a dynamic tool for EMMA k-sensitivity analysis. A screenshot of the dynamic tool is provided in Figure 10.

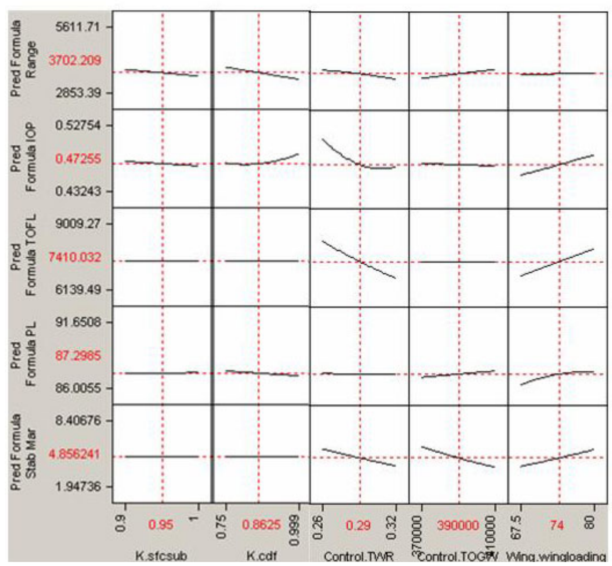

Figure 10. Screenshot of sensitivity dynamic visualization tool

SUMMARY

This paper outlined the process by which an Efficient Multi-Mach Aircraft was subjected to a sensitivity analysis between advanced concept program goals and performance objectives. The process addressed the definition, taxonomy selection and optimization of a current technology concept and an advanced concept using a multi-objective genetic algorithm and Powell's method. A dynamic visualization tool for the sensitivity analysis was constructed using response surface equations allowing for the identification of high-impact k-factors that support the selection of technologies for future technology portfolio assessments of the EMMA.

ACKNOWLEDGEMENTS

This research was supported by NASA Langley Research Center under contract number NAS3-00179/NNL04AD06T. The Authors would like to thank the following people for their support and assistance: Mr. Michael Buonanno from the Aerospace Systems Design Laboratory, and Mr. Neil Kuhn from NASA Langley Research Center.

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